available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/burns

Review

Lightning injury: A review☆

Amber E. Ritenour [a,b], *Melinda J. Morton* [a], *John G. McManus* [a], *David J. Barillo* [a], *Leopoldo C. Cancio* [a,*]

[a] *U.S. Army Institute of Surgical Research, Fort Sam Houston, TX 78234, United States*
[b] *Brooke Army Medical Center, Fort Sam Houston, TX 78234, United States*

ARTICLE INFO

Article history:
Accepted 5 November 2007

Keywords:
Lightning
Burns

ABSTRACT

Lightning is an uncommon but potentially devastating cause of injury in patients presenting to burn centers. These injuries feature unusual symptoms, high mortality, and significant long-term morbidity. This paper will review the epidemiology, physics, clinical presentation, management principles, and prevention of lightning injuries.

Published by Elsevier Ltd and ISBI

Contents

1. Introduction

Injuries secondary to lightning strike are rare, and feature an unusual presentation, high mortality, and significant long-term morbidity. The American Burn Association recommends referral to a burn center for victims of lightning strike; thus, burn-care providers should be familiar with the characteristics and treatment of these injuries. This paper will review the epidemiology, physics, clinical presentation, management

☆ The opinions or assertions contained herein are the private views of the authors, and are not to be construed as official or as representing the views of the Department of the Army or Department of Defense.

* *Corresponding author*. Tel.: +1 210 916 3301.
E-mail address: lee.cancio@us.army.mil (L.C. Cancio).

0305-4179/$34.00. Published by Elsevier Ltd and ISBI
doi:10.1016/j.burns.2007.11.006

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **01 AUG 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Lightning injury: a review**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Ritenour A. E., Morton M. J., McManus J. G., Barillo D. J., Cancio L. C.,**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **United States Army Institute of Surgical Research, JBSA Fort Sam Houston, TX 78234**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

principles, and prevention of lightning injuries for burn-care providers.

2. Epidemiology

Lightning strikes the earth more than 100 times each second or 8 million times per day. About 50,000 thunderstorms occur each day that may result in fires and injury (Okafor, 2005 #17708) [91]. Worldwide, lightning strike density is highest in Africa, where some regions experience more than 50 lightning strikes/km^2 each year [1]. The risk of being struck by lightning is a function of strike and population densities, as well as terrain features that may protect or expose occupants of a geographical area.

Lightning is the second leading cause of weather-related death in much of the world. The epidemiology of lightning injury, much of which has been published in the meteorological rather than the medical literature, is well described only for certain areas of the world [2,3]. Furthermore, underreporting significantly affects the data. For example, Cherington found underreporting of injuries by 49% (51 vs. 100 cases) and of deaths by 11% (8 vs. 9) for the U.S. state of Colorado during 1993–1995, when comparing the National Oceanic and Atmospheric Administration (NOAA) *Storm Data* database (based mainly on newspaper reports) to medical and death-certificate databases [4]. Worldwide mortality due to lightning is estimated to be 0.2–1.7 deaths/million people [5,6]. A South African study noted a higher rate of 6.3 deaths/million inhabitants for the Highveld, a region consisting predominantly of urban poor [7]. For an average person in the U.S., the lifetime risk is roughly 1 in 3000 of being struck and 1 in 35,000 of being killed by lightning [8]. Lightning-related mortality data are summarized in Table 1.

There are important regional, seasonal, and temporal differences in the risk of lightning injury. In the U.S., the largest number of deaths occurs in two southern states with coastlines along the Gulf of Mexico: Texas and Florida [2,6,9]. In the case of Florida, the large number reflects factors such as a high annual number of thunderstorm days and a high ground-flash density. Many victims in that state are injured in or near water [9]. On the other hand, during 1968–1985, the highest number of deaths per inhabitants in the U.S. was reported for the rural Rocky Mountain state of Wyoming, at 1.96 million^{-1}, and New Mexico at 1.70, whereas the national average was 0.61 million^{-1} [10].

Table 1 – Summary of recent lightning-related mortality for several countries

Country	Year(s)	Deaths/year	Reference
Australia	1957–1969	2.9	[13]
Canada	1991–1995	5.4	[82]
Germany	1991–1993	6.3	[46]
England and Wales	1980s	4.2	[17]
Singapore	1956–1979	3.3	[14]
South Africa (Highveld)	1997–2000	9.5	[7]
Switzerland	1988–1992	2.4	[46]
U.S.	1968–1985	106	[10]

Lightning injuries peak during the summer months throughout much of the world. The month of July consistently features the largest number of casualties in the U.S. [2]. In India, the peak months are the monsoon season of June–September [11]. The opposite pattern is noted south of the equator in Australia [12,13] and South Africa [7]. In Singapore, an equatorial country, two peaks are observed in April and November [14]. Most injuries take place in the afternoon (1200–1800 h local time) [2,7].

There have been significant changes over time in the risk of lightning injury and death in those countries with long-term data. Despite rising population, the number of lightning deaths in the U.S. decreased from 377 during 1891–1894, to 239 during 1991–1994 [15]. From the 1950s until the 1990s, there was a slight decrease in the per person risk of lightning injury or death [16]. A likely explanation for this finding is a decrease in the number of individuals involved in farming, and an increase in the proportion of the population living in an urban setting. Similar long-term decreases in the number of lightning injuries and fatalities were observed in England and Wales over the period 1852–1990. In that region, the mean annual number of lightning deaths decreased from 20.5 for 1852–1859, to 4.2 for 1980–1999. This occurred despite a doubling of the population, implying an eightfold decrease in the risk of death [17].

Has improved medical care, to include emergency medical services systems, changed the survival prospects of patients struck by lightning? One paper based on the U.S. *Storm Data* database concluded that the ratio of injuries to deaths increased from two in 1959 to about seven in 1994; of course, changes in reporting cannot be excluded [16]. Although the annual number of injuries in the U.S. is typically cited as 300 and the annual number of deaths as 100 [10,16], the National Weather Service of the U.S. currently estimates about 70 deaths/year in the U.S., and a 10% mortality rate [18]. A recent query of the National Trauma Data Bank (NTDB Version 5) revealed 95 cases and 9 deaths for a similar mortality rate (9.5%) [8]. In one report, the U.S. military reported 350 injuries but only 1 death during 1998–2001; however, 44 casualties were injured in a single event [19].

Lightning injuries and deaths occur most often in individuals who work outside or participate in outdoor recreational activities. Thus, men are five times more likely to be struck by lightning than are women [20], and military personnel appear to be at particular risk. Young people (ages 10–29 years) are at greatest risk in several series [9,10,13,14]. In one U.S. series, 25% of lightning deaths were work-related; the leading occupations involved were farming and construction [21]. Over time, some regions have noted a decrease in outdoor-work-related injuries, and an increase in outdoor-recreation-related injuries [16,17]. However, it is noteworthy that 32% of injuries in the above-mentioned NTDB review occurred indoors [8]. Improvements in building design likely reduced the number of indoors injuries between the 1890s and 1990s [15]. These improvements have included not only the widespread implementation of Benjamin Franklin's 1752 invention, the lightning rod [22], but also improvements in grounding due to installation of plumbing, telephone lines, and electric wiring [15]. Lightning injury has been reported in individuals riding bicycles, motorcycles, or boats [23]. Light-

ning has also struck aircraft in flight, resulting in fatalities; structural improvements have made aircraft safer from lightning over the years [24].

3. Lightning physics

Lightning is generated when the voltage difference between a cloud and the ground or another object exceeds 2 million V/m. At this point, arcing occurs. Factors that determine the site and severity of electric trauma include the magnitude of energy delivered; voltage; resistance to current flow; type of current; duration of contact with the current source; and current pathway. The electric current involved in lightning strikes is direct current (DC), as opposed to the alternating current (AC) that is responsible for the majority of household and industrial electric injuries. The amount of DC current delivered by a lightning strike, on the order of 30,000–50,000 A, is far greater than that produced by AC electricity. The duration of exposure is generally much shorter, approximately 10–100 ms. This current causes the release of a tremendous amount of heat, raising temperatures to approximately 30,000 K. This brief temperature effect causes a ‘‘thermoacoustic blast wave,’’ or thunder. The overpressure generated by thunder at the source may approach 100 atm [25–27].

The various interactions of lightning with the body produce a mortality rate of 10–30% and a 76% risk of long-term sequelae in survivors [28]. Lightning may cause injury in several ways [29,30]:

- *Direct strike*: Casualties may sustain a direct strike, which is often fatal.
- *Contact injury* occurs when lightning strikes an object, such as a car or metal pole, which the victim is touching.
- *Side flash* involves current splashing from a nearby object or person onto the victim.
- *Ground current*: When lightning strikes the ground near a victim, ground current passes from the strike point, through the ground, and into the victim.
- *Upward streamer*: In a case report, passage of lightning from the victim upwards, as a weak upward streamer, has been described [29].
- *Blast injury*: Finally, lightning’s blast effect (thunder) may cause either primary or tertiary blast injury. Primary blast injury is often manifested as ruptured tympanic membranes, whereas tertiary blast injury may present as blunt trauma when the victim falls or is thrown.

When an individual is struck by lightning, the primary current arc travels outside the body, a phenomenon known as ‘‘flashover.’’ Some authors hypothesize that this phenomenon is protective, causing the current to flow over, rather than through, the body [31,32]. However, this immense current likely generates large magnetic fields perpendicular to the body surface, which in turn induce secondary electric currents within the body. These secondary currents may cause cardiac arrest and other internal injuries [25]. In fact, induced magnetic currents may explain those cases in which cardiac arrest occurs following lightning strike in the absence of any other signs of injury [33]. When lightning hits the ground, current spreads out from the contact point such that if a casualty is standing nearby with feet apart, the potential difference between the feet may be in the range of 1500 V [25]. Lightning injuries are thus more severe when a person’s feet are apart than when they are close together [34]. When lightning directly strikes a victim’s upper body, a very large potential difference between the upper and lower body is established. A brief, large current flow will result. The duration is generally not sufficient to cause Joule heating, as in high-voltage electric injuries, but it is sufficient to damage muscle and nerve cells by other mechanisms such as electroporation.

Electroporation, also known as electropermeabilization, features reorganization of lipids in the cell membrane into ‘‘pores’’ as a result of an imposed transmembrane potential (Fig. 1). This results in a large increase in membrane permeability that significantly augments the work necessary to maintain transmembrane concentration gradients. When cellular metabolic energy stores become depleted, ATP-driven ion pumps can no longer compensate for the rapid diffusion of ions through the damaged cell membrane. At this point, if the membrane does not seal itself, cell death occurs. Skeletal muscle and nerve cells are especially susceptible to electroporation because of their size: cell length is directly proportional to transmembrane potential in these cell types. Some authors suggest that the delayed presentation of neurological sequelae following lightning injury is due largely to the effects of electroporation over time [25].

Ball lightning is an unusual form of lightning which deserves brief comment. Ball lightning is seen during lightning storms as a moving, floating ball ranging in size from that of a golf ball to that of a basketball. A variety of theories have been proposed to explain ball lightning. Since it is a low-energy phenomenon, it rarely causes death; but in case reports it has been associated with long-term neurological sequelae [35–37].

4. Clinical presentation and care

Lightning causes death in 10–30% of casualties, and results in permanent disability in the majority of survivors. Many vital structures may be affected. Persons struck by lightning usually show evidence of multiorgan derangement, with the most dramatic effects involving the central nervous and cardiovascular systems.

4.1. *Cardiopulmonary support*

In several reports, the majority of deaths from lightning injury appear to be either immediate [7], or, alternatively, the result of immediate cardiopulmonary arrest followed by unsuccessful resuscitation [9]. The primary cause of death following lightning strike is asystolic cardiac arrest or ventricular fibrillation [6,34,38,39]. Lightning causes a massive DC ‘‘countershock’’, which simultaneously depolarizes the entire myocardium. At the same time, respiratory arrest may occur due to chest muscle paralysis and suppression of medullary respiratory centers. Even if cardiac automaticity enables spontaneous recovery of electrical activity following the lightning strike, respiratory arrest may cause secondary hypoxic cardiac arrest [39,40]. Cooper found that cranial burns

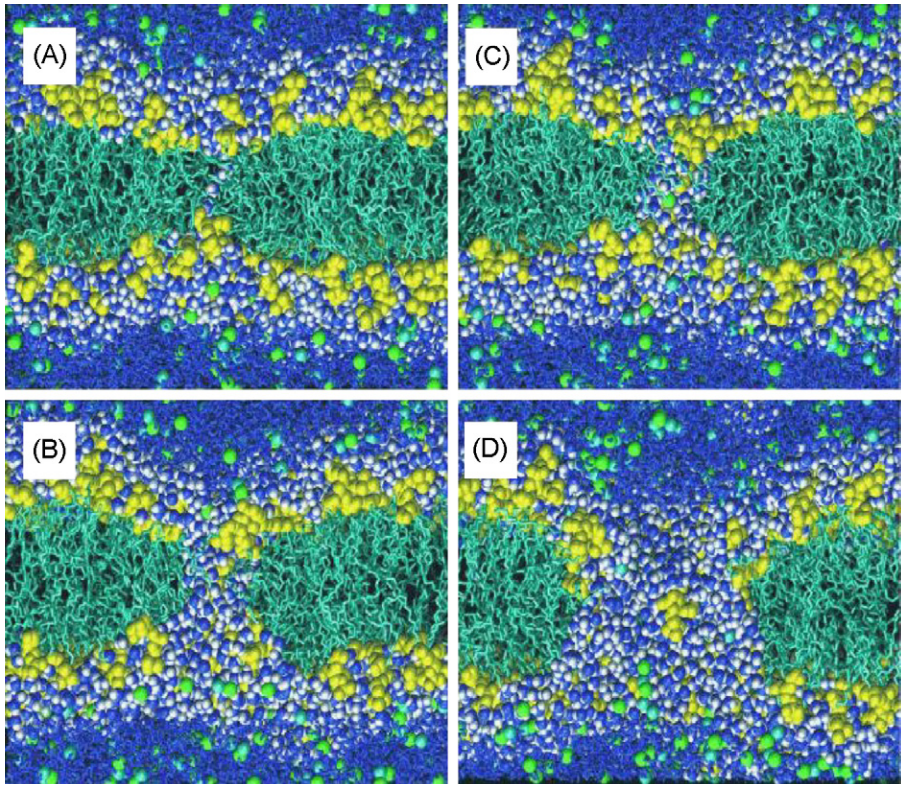

Fig. 1 – Electroporation. Computer simulation of electropore formation in a phospholipid (DOPC) bilayer, with an applied electrical field of 0.5 V/nm in the presence of 1 M NaCl at (A) 5330 picoseconds (ps), (B) 5450 ps, (C) 5500 ps, and (D) 5700 ps. The lipid headgroups are shown in yellow, the chains in cyan, chloride ions space-filling in green, sodium ions in cyan; water is shown as dark blue and white space-filling in the interface region and the pore, and as dark blue bonds elsewhere. The potential is positive at the top of each photograph relative to the bottom. Reprinted with permission from Tieleman [80], licensee BioMed Central Ltd. (Open Access Article). Available at www.biomedcentral.com/1471-2091/5/10 [accessed October 2007]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

or leg burns were predictive of increased mortality. Also, she noted that death was unlikely in the absence of immediate arrest [41].

Lightning injury is also associated with massive catecholamine release through an unknown mechanism, which may be manifested (in patients who do not arrest) by hypertension, tachycardia, non-specific EKG changes, and contraction-band myocardial necrosis. Myocardial infarction, however, is unusual [42]. Blunt trauma may explain cases of myocardial contusion in lightning trauma patients.

Patients who have experienced a lightning strike should be treated as if they had sustained high-energy blunt trauma. First responders should rapidly assess airway, breathing, and circulation, and should strongly consider full spine immobilization. The American Heart Association (AHA) and the European Resuscitation Council have published recommendations for the immediate cardiopulmonary resuscitation of lightning victims; the usual Basic Life Support (BLS), Advanced Cardiac Life Support (ACLS), and defibrillation techniques are recommended [38–40,43]. In addition, respiratory arrest – due to respiratory center suppression and thoracic muscle spasm – may persist even after return of circulation, and ventilation must be supported. Lightning patients may respond to resuscitation even when they appear dead, and even when the interval between injury and resuscitation is prolonged. Thus, the AHA recommends ‘‘vigorous resuscitative measures. . .even for those who appear dead on initial evaluation.’’ This policy is supported by several facts: there are reports of excellent recovery after lightning-induced cardiac arrest; the amount and duration of charge are unknown; and most victims are young and without heart disease [40]. Some patients may have no post-arrest morbidity if promptly resuscitated [44].

Lightning may strike several people at once, creating a mass-casualty situation [44–46]. The largest such single incident occurred in Michigan in 1975, injuring 90 of 500 persons at a campground [47]. A counterintuitive approach to triage of multiple lightning victims was proposed by Taussig [48]. According to this concept, patients who are apparently dead should be resuscitated first. This is based on the observation that such casualties respond well to cardiopulmonary resuscitation, and may only require respiratory support [30].

Patients with lightning injuries may require fluid resuscitation, particularly if hypotension and/or rhabdomyolysis are present. The fluid resuscitation requirements of these patients

are ill-defined, but may be proportionate to the amount of underlying muscle damage, if any—in a manner analogous to that of high-voltage electric injury [49]. Such underlying tissue damage is less common following lightning injury than following high-voltage electric injury, however. The presence of hypotension should also prompt a search for sources of bleeding secondary to blunt trauma, such as intra-abdominal injury [46,50–52].

4.2. *Skin lesions*

There are four types of skin lesions that can result from lightning strike: linear, punctate, ''feathering,'' and thermal. Linear burns preferentially follow areas of high sweat concentration, such as under the breasts and arms, and down the middle of the chest (Fig. 2). They are generally small, from 1 to 4 cm in diameter. They may be present initially, or develop over several hours, and are thought to be due to vaporization of water on the skin's surface [53].

Punctate burns are small, multiple, closely spaced circular burns. Some may be full-thickness, but because of their small size (generally less than 1 cm) they rarely require grafting. The ''tip-toe sign'' is one example of a punctate burn; it consists of small circular full-thickness burns of the tips of the toes and the sides of the soles of the feet [7,44].

''Feathering'' lesions do not represent a thermal injury, and the epidermis and dermis are normal. Lichtenberg figures, also known as keraunographic markings (Fig. 3), are one example of this type of lesion. Lichtenberg figures are pathognomonic for lightning, but are often not present. They have been described as fern-like, branching, arborizing, serpiginous, or fractal. Upon pathophysiologic examination they consist of extravasation of blood in the subcutaneous tissues [54]. Lichtenberg figures are evanescent, lasting several hours, and usually disappear without known residual effect. No specific treatment is required [55].

Thermal injury may occur if the patient is wearing metal objects (e.g. zippers), or if clothing ignites [53].

Patients with lightning injury rarely suffer from extensive tissue destruction or large cutaneous burns. Thus, lightning burns – in contrast to other electric injuries – should generally be treated expectantly. They are usually superficial, and tend to heal quickly [56]. The burns caused by lightning are typically small, i.e. less than 20% of the total body surface area, and confined to the skin. In one series of victims of lightning strike, although 89% sustained cutaneous injuries, only 5% of these were full-thickness [41]. Standard wound care procedures should be employed for lightning-associated cutaneous burns [25,57,58].

Fig. 2 – Linear streak on back and buttocks of a 14-year-old male treated at the U.S. Army Institute of Surgical Research after a lightning struck his house.

Fig. 3 – Keraunographic marking (Lichtenberg figure) on shoulder and chest. Reprinted with permission from Bartholome et al. [81].

The superficial nature of most lightning burns should not, however, be taken as evidence that an individual lacks more serious injury; the most profound and lasting injuries associated with lightning exposure are often neurologic and cardiac in nature. In a minority of patients, fatal lightning injury may occur in the absence of burns or other obvious external or internal injury. This finding has been attributed to the induction of current by strong magnetic fields, sufficient to cause cardiac arrest [25,41].

4.3. *Muscle injury*

Extremities may appear cool, blue, or pulseless due to transient vasospasm [59]; this phenomenon may also feature keraunoparalysis (see below). Emergent fasciotomy and debridement should be considered for patients with elevated compartment pressures or other clear evidence of intramuscular compartment syndrome [53]. However, steady improvement of the cool extremity, with subsequent return of pulses, is the more likely outcome. Although extensive muscle damage following lightning strike is unusual, patients with myoglobinuria should be

treated as for high-voltage electric injury, with aggressive fluid resuscitation and consideration of mannitol if pigment does not clear [49].

4.4. Central nervous system abnormalities

Central nervous system (CNS) injury is common in lightning victims. The neurological effects of lightning injury have been classified by Cherington [60]. These four groups of CNS injury include: Immediate and Transient, Immediate and Prolonged/Permanent, Possible Delayed Neurological Syndromes, and Trauma from Falls or Blast.

Group 1 neurological effects (Immediate and Transient) are very common, and include loss of consciousness in 75%; confusion, amnesia, and headaches; paresthesias in 80%; weakness in 80%; and keraunoparalysis [60,61]. Keraunoparalysis (Charcot's paralysis) is a neurological disorder specific to lightning victims which features transient paralysis, often predominantly affecting the lower extremities, and accompanied by loss of sensation; it lasts one to several hours and then resolves. It is hypothesized that keraunoparalysis is a result of intense catecholamine release because of the accompanying pallor, intense vasoconstriction, and hypertension often seen in these patients. Certainly, patients with neurologic deficits should be assumed to have spinal injury rather than keraunoparalysis, until proven otherwise by diagnostic imaging [34].

Group 2 neurological effects (Immediate and Prolonged/Permanent) feature the sequelae of significant neurological injury, and include hypoxic ischemic neuropathy; intracranial hemorrhage (to include subarachnoid and intracerebral hemorrhage); post-arrest cerebral infarction, especially of watershed areas; and cerebellar syndromes. Spinal and peripheral nerve injuries are uncommon, in contrast to high-voltage electric injury [49].

Group 3 neurological effects (Possible Delayed Neurological Syndromes) are those which may be related to lightning, but which present in delayed fashion. These include motor neuron diseases and movement disorders.

Finally, Group 4 injuries (Trauma from Falls or Blast) include subdural and epidural hematomas and subarachnoid hemorrhage.

In addition, lightning injury may be associated with long-term neuropsychological impairment. Common complaints include fatigue, lack of energy, poor concentration, irritability, and emotional lability. Post-traumatic stress disorder is another common complaint, occurring in about 30% of patients after lightning injury [62]. Cognitive testing may reveal memory, attention, and visual-reaction-time abnormalities. Some patients will meet criteria for depression. Of course, these effects may cause significant vocational and interpersonal difficulty [63], and early neuropsychiatric intervention is recommended.

On CT or MRI, cerebral edema is a common finding. Neuropathological findings associated with CNS injuries in groups 2–4 can be seen on CT and MRI and are summarized in Table 2.

4.5. Opthalmologic and otologic findings

Considering the blast overpressures generated by lightning strike, it is not surprising that patients frequently present with tympanic membrane rupture, and more rarely with more severe otologic injuries such as sensorineural deafness or vestibular injury. In fact, lightning transmission through a telephone network may occur. If the casualty is using the telephone during such an event, a 150–160 dB shock wave may be generated, causing tympanic membrane rupture which is frequently unilateral. A 1989 report indicated that 60 patients annually in Australia are injured by lightning while using the telephone [64]. Tympanic membrane rupture, which is present in 50% of lightning strike survivors [65], should be identified with early consultation of otolaryngology and immediate otomicroscopy, aseptic aspiration toilet, and determination of

Table 2 – Summary of recent case reports of CT/MRI findings in patients after lightning injury

Age/sex	Presentation	Study	Findings	Outcome	Reference
20/M	Unconscious	CT	Subarachnoid hemorrhage basal ganglia	Died	[83]
11/M	Unconscious, hemiplegia	CT	Hematoma, basal ganglia	Improved	[84]
45/M	Unconscious, apneic	CT	Cerebral edema	Improved	[85]
15/M	Cardiopulmonary arrest	CT	Subdural hematoma	Improved	[86]
15/M	Left hemiplegia	MRI	Parietal infarction	Improved	[87]
33/M	Ataxia	MRI	Cerebellar atrophy	Improved	[87]
38/M	Cardiac arrest	MRI	Hypoxic brain injury	Died	[87]
46/M	Ataxia, dysarthria, difficulty obeying commands, attention deficit	MRI	Multiple small foci of hyperintensity in the supratentorial white matter	Improved	[88]
48/M	LUE paresthesia and finger-to-nose ataxia, attention deficit, frontal lobe function	MRI	Multiple small hyperintense lesions consistent with demyelination in the periventricular area and cerebellar hemisphere	Stable	[37]
58/M	Unconscious, transient quadriplegia, paresthesia and weakness of hands/fingers, foot	MRI	Hyperintense lesions within the posterolateral C1–C3 spinal cord, degenerative changes at C3–C4 consistent with delayed myelopathy	Improved	[89]

Adapted, in part, from Cherington, with permission [90].

the need for eversion or repair of perforation edges [66,67]. Conservative therapy is generally recommended in small or simple perforations, with surgery being reserved for more severe injuries. Bed rest with elevation of the head to decrease cerebrospinal fluid pressure may decrease leakage of perilymph [68]. Occasional cases of bilateral perilymphatic fistulas from a lightning strike have been reported [65,68]. Other neuro-otologic findings have included transient vertigo, tinnitus, basilar skull fracture, and burns to the external auditory canal [69].

A wide variety of eye injuries can be caused by lightning strike. The most common of these is ''lightning cataract.'' As with high-voltage electric injury, presentation of cataracts may be delayed. A recent case report described cataracts that did not appear in one lightning victim until 4 years after the lightning strike; this is likely due to the fact that initial changes are in the periphery and often missed in the acute setting [70]. Proposed mechanisms for cataract formation include passage of electric current through the lens, heat, vasoconstriction, and blunt trauma. Prompt ophthalmology consultation is indicated for all survivors of lightning strike. Some authors have used intravenous steroids for the treatment of optic-nerve injury in these patients. Other ophthalmologic sequelae of lightning injury include corneal burns, intraocular hemorrhage or thrombosis, uveitis, chorioidoretinitis, iridocyclitis, hyphema, and orbital fractures. It is important to bear in mind that dilated or non-reactive pupils are not considered a reliable sign of brain death in the early post-injury period [71–73].

5. Prevention

Clearly, prevention of these highly lethal injuries is paramount. A high level of precaution for individuals working or engaging in recreational activities outdoors during the thunderstorm season must be observed. Travel guides and weather-related websites are good resources for determining the timing and duration of rainy seasons for various locations worldwide. Although lightning is associated with cumulonimbus rain clouds, it may precede the rainstorm and has been known to strike with blue skies overhead (a ''bolt from the blue'') [6,74,75]. No rain was falling during 21% of lightning deaths in the Florida study for which weather data were available [9]. Lightning may also occur, infrequently, during snowstorms. A harbinger of lightning during a snowstorm is the appearance of graupel, also known as soft hail or snow pellets [76].

When thunder is heard, personnel should seek shelter in a building or enclosed vehicle. (The latter protect not because of insulation by rubber tires, but because the metal exterior acts like a Faraday cage, conducting current around the vehicle [23].) Trees or tall objects, high ground, water, open spaces, and metal objects should be avoided [77]. In particular, some individuals increase their risk of injury by erroneously seeking shelter under isolated trees during thunderstorms [9,47]. A remarkable 60% of Florida lightning injuries occurred when the victim was holding something metallic [9]. Ungrounded buildings such as shacks and huts should be avoided [14]. Indoors during a thunderstorm, appliances should be turned off and the telephone should not be used [5,64].

During outdoor activities, the ''30–30 rule'' describes the following two precautions. A flash-to-thunder interval of less than 30 s places personnel at risk for lightning strike; personnel should stay in shelter for 30 min after the last lightning and thunder are noted. There is a relatively safe triangle near walls, no closer than 1 m to the wall, and no farther from the wall than the wall's height. When stranded in the open, it is best to crouch with the feet and knees together; do not lie flat. An impending hit may be signaled by a crackling sound, a visible glow (St. Elmo's Fire), a tingling sensation, and/or hair standing on end. This should prompt one to crouch immediately with feet together [31].

Several popular myths exist about lightning. They include:

- ''Lightning never strikes the same place twice''.
- ''It is dangerous to touch a lightning victim''.
- ''Lightning always hits the highest object''.

All of these myths are false [31].

6. Resources

Resources for survivors of lightning injury include Lightning Strike and Electric Shock Survivors, International (http://www.lightning-strike.org/), which has been helpful for many survivors and their families with long-term sequelae [78]. Additional information is available from the Lightning Data Center at St. Anthony Hospitals, Denver, CO, USA (http://www.stanthonyhosp.org/), the National Oceanic and Atmospheric Administration (NOAA) of the U.S. government (http://www.noaa.gov/), and the Lightning Injury Research Program at the University of Illinois at Chicago (http://www.uic.edu/labs/lightninginjury/index.html). For the United Kingdom, the Tornado and Storm Research Organisation can be accessed (http://www.torro.org.uk/TORRO/index.php). Vaisala Inc. (Tuczon, AZ) operates the U.S. National Lightning Detection Network and the Canadian Lightning Detection Network. These consist of a network of lightning sensors, providing both real-time notification of thunderstorm activity and retrospective data on lightning strikes (http://www.vaisala.com/weather/products/lightning).

7. Conclusion

In summary, patients with lightning injury, like those with high-voltage electric injury, should be considered to have sustained high-energy blunt trauma with certain additional unique features. Airway and cardiopulmonary status must be stabilized and maintained, and patients may require spinal precautions. They should be thoroughly evaluated for blunt trauma, as if they had sustained a high-speed motor-vehicle crash. Large-bore IV access should be obtained, and fluid resuscitation should begin in patients who are hypotensive. Treatment is generally conservative, but some patients require urgent fasciotomy. In the long term, skin grafting may be required. They should be evaluated for tympanic membrane rupture and other blast injuries. They also merit cardiac monitoring. Early ophthalmologic consultation is

mandatory. Long-term neuropsychological follow-up is justified. Because of the high mortality and complexity of lightning injury, its rarity, and its long-term sequelae, these patients should be cared for by a multidisciplinary Burn Center team [79].

Acknowledgement

This work was funded in part by the Combat Casualty Care research program of the US Army Medical Research and Materiel Command, Ft. Detrick, MD.

Conflict of interest

None.

REFERENCES

[1] Anonymous. Where lightning strikes. National Aeronautics and Space Administration (n.d.). Available at: http://visibleearth.nasa.gov/view_rec.php?id=2264 [accessed October 2007].
[2] Holle RL, Lopez RE, Curran EB. Distributions of lightning-caused casualties and damages since 1959 in the United States. Presented at the 11th conference on applied climatology, American Meteorological Society, January 1999. Available at http://www.uic.edu/labs/lightninginjury/holle30yrs.html [accessed October 2007].
[3] Holle RL. Bibliography on safety and demographics of lightning victims (unpublished document). Oro Valley, AZ: Holle Meteorology & Photography; 2006.
[4] Cherington M, Walker J, Boyson M, Glancy R, Hedegaard H, Clark S.In: Closing the gap on the actual numbers of lightning casualties and deaths. Presented at the 11th conference on applied climatology. Boston, MA: American Meteorological Society; 1999. p. 379–80.
[5] Aslar AK, Soran A, Yidiz Y. Epidemiology, morbidity, mortality and treatment of lightning injuries in a Turkish burns unit. Int J Clin Pract 2001;55:502–4.
[6] Wetli CV. Keraunopathology. An analysis of 45 fatalities. Am J Forensic Med Pathol 1996;17(2):89–98.
[7] Blumenthal R. Lightning fatalities on the South African Highveld: a retrospective descriptive study for the period 1997 to 2000. Am J Forensic Med Pathol 2005;26(1):66–9.
[8] Fantus RJ. Zeus on the 18th hole. Bull Am Coll Surg Dec 2006;91:34–5.
[9] Duclos PJ, Sanderson LM, Klontz KC. Lightning-related mortality and morbidity in Florida. Public Health Rep 1990;105(3):276–82.
[10] Duclos PJ, Sanderson LM. An epidemiological description of lightning-related deaths in the United States. Int J Epidemiol 1990;19(3):673–9.
[11] Nizamuddin S. Deaths caused by lightning in India. Weather 1992;47:366–7.
[12] Coates L, Blong R, Siciliano F. Lightning fatalities in Australia, 1824–1991. Nat Hazard 1993;8:217–33.
[13] Prentice SA. Lightning fatalities in Australia. IEA Electr Eng Trans 1972;8:55–63.
[14] Pakiam JE, Chao TC, Chia J. Lightning fatalities in Singapore. Meteor Mag 1981;110:175–87.
[15] Holle RL, Lopez RL, Navarro BC. U.S. lightning deaths, injuries, and damages in the 1890s compared to the 1990s (NOAA Technical Memorandum OAR NSSL-106). Norman, OK: National Severe Storms Laboratory, April 2001. Available at http://www.nssl.noaa.gov/papers/techmemos/NSSL-106/index.html [accessed October 2007].
[16] Curran EB, Holle RL, Lopez RE. Lightning casualties and damages in the United States from 1959 to 1994. J Climate 2000;13:3448–64.
[17] Elsom DM. Deaths caused by lightning in England and Wales, 1852–1990. Weather 1993;48:83–90.
[18] Anonymous. Medical aspects of lightning. National Weather Service (n.d.). Available at http://www.lightningsafety.noaa.gov/medical.html [accessed October 2007].
[19] Centers for Disease Control and Prevention. Lightning-associated injuries and deaths among military personnel–United States, 1998–2001. Morb Mort Wkly Rep 2002;51:859–62.
[20] Center for Disease Control and Prevention. Lightning-associated deaths—United States, 1980–1995. Morb Mort Wkly Rpt 1998;4:391–4.
[21] Adekoya N, Nolte KB. Struck-by-lightning deaths in the United States. J Environ Health 2005;67(9):45–50.
[22] Krider EP. Benjamin Franklin and lightning rods. Phys Today Jan 2006;59:42.
[23] Cherington M. Lightning and transportation. Semin Neurol 1995;15(4):362–6.
[24] Cherington M, Mathys K. Deaths and injuries as a result of lightning strikes to aircraft. Av Space Environ Med 1995;66(7):687–9.
[25] Bier M, Chen W, Bodnar E, Lee RC. Biophysical injury mechanisms associated with lightning injury. Neurorehabilitation 2005;20(1):53–62.
[26] Lee RC. Injury by electrical forces: pathophysiology, manifestations, and therapy. Curr Probl Surg 1997;34(9):677–764.
[27] Lee RC, Zhang D, Hannig J. Biophysical injury mechanisms in electrical shock trauma. Annu Rev Biomed Eng 2000;2:477–509.
[28] Whitecomb D, Martinez JA, Daberkow D. Lightning injuries. South Med J 2002;95:1331–4.
[29] Cooper MA. A fifth mechanism of lightning injury. Acad Emerg Med 2002;9(2):172–4.
[30] Zafren K, Durrer B, Herry JP, Brugger H. Lightning injuries: prevention and on-site treatment in mountains and remote areas. Official guidelines of the International Commission for Mountain Emergency Medicine and the Medical Commission of the International Mountaineering and Climbing Federation (ICAR and UIAA MEDCOM). Resuscitation 2005;65(3):369–72.
[31] Epperly TD, Stewart JR. The physical effects of lightning injury. J Fam Pract 1989;1–8.
[32] Cooper MA. Disability, not death, is the main problem with lightning injury. Address presented at the National Weather Association annual meeting, October 1998. Available at http://www.uic.edu/labs/lightninginjury/Disability.pdf [accessed April 2007].
[33] Cherington M, Wachtel H, Yarnell PR. Could lightning injury be magnetically induced? Lancet 1998;351(9118):1788.
[34] Andrews CJ, Darveniza M, Mackerras D. Lightning injury—a review of clinical aspects, pathophysiology, and treatment. Adv Trauma 1989;4:241–88.
[35] Cherington M, Yarnell PR. Ball lightning encephalopathy. J Burn Care Rehab 2003;24(3):175.
[36] Selvaggi G, Monstrey S, von Heimburg D, Hamdi M, Van Landuyt K, Blondeel P. Ball lightning burn. Ann Plast Surg 2003;50(5):541–4.
[37] Cherington M, Yarnell PR, Lane J, Anderson L, Lines G. Lightning-induced injury on an airplane: coronal

discharge and ball lightning. J Trauma 2002;52(3): 579–81.
[38] Kloeck W, Cummins RO, Chamberlain D, Bossaert L, Callahan V, Carli P, et al. Special resuscitation situations: an advisory statement from the International Liaison Committee on Resuscitation. Circulation 1997;95(8): 2196–210.
[39] Anonymous. 2005 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Part 10.9: electric shock and lightning strikes. Circulation 2005;112 [IV-154–IV-5].
[40] Anonymous. Part 8: advanced challenges in resuscitation. Section 3: special challenges in ECC. 3G: electric shock and lightning strikes. European Resuscitation Council. Resuscitation 2000;46(1–3):297–9.
[41] Cooper MA. Lightning injuries: prognostic signs for death. Ann Emerg Med 1980;9:134–8.
[42] Jensen PJ, Thomsen PE, Bagger JP, Norgaard A, Baandrup U. Electrical injury causing ventricular arrhythmias. Br Heart J 1987;57(3):279–83.
[43] Anonymous. Guidelines for cardiopulmonary resuscitation and emergency cardiac care. Emergency Cardiac Care committee and subcommittees, American Heart Association. Part IV. Special resuscitation situations. JAMA 1992;268(16):2242–50.
[44] Fahmy FS, Brinsden MD, Smith J, Frame JD. Lightning: the multisystem group injuries. J Trauma 1999;46(5):937–40.
[45] Carte AE, Anderson RB, Cooper MA. A large group of children struck by lightning. Ann Emerg Med 2002;39(6):665–70.
[46] Graber J, Ummenhofer W, Herion H. Lightning accident with eight victims: case report and brief review of the literature. J Trauma 1996;40(2):288–90.
[47] Ferrett RL, Ojala CF. The lightning hazard in Michigan. Mich Acad 1992;24:427–41.
[48] Taussig HB. ‘‘Death’’ from lightning—and the possibility of living again. Ann Intern Med 1968;68(6):1345–53.
[49] Cancio LC, Jimenez-Reyna JF, Barillo DJ, Walker SC, McManus AT, Vaughan GM. One hundred ninety-five cases of high-voltage electric injury. J Burn Care Rehab 2005;26(4):331–40.
[50] Jain S, Bandi V. Electrical and lightning injuries. Crit Care Clin 1999;15(2):319–31.
[51] Alcock R, Fletcher-Jones HC. Abdominal injury from lightning. Lancet 1949;1:823–5.
[52] Aslan S, Aydinli B, Ocak T, Akcay M. Lightning: an unusual etiology of gastrointestinal perforation. Burns 2005;31(2):237–9.
[53] O’Keefe Gatewood M, Zane RD. Lightning injuries. Emerg Med Clin North Am 2004;22(2):369–403.
[54] Resnik BI, Wetli CV. Lichtenberg figures. Am J Forensic Med Pathol 1996;17(2):99–102.
[55] Cherington M. James Parkinson: links to Charcot, Lichtenberg and lightning. Arch Neurol 2004;61(6):977.
[56] Maghsoudi H, Adyani Y, Ahmadian N. Electrical and lightning injuries. J Burn Care Res 2007;28(2):255–61.
[57] Purdue GF, Hunt JL. Electrical injuries. In: Herndon DN, editor. Total Burn Care. 2nd edn., London: Saunders; 2002.
[58] Amy BW, McManus WF, Goodwin Jr CW, Pruitt Jr BA. Lightning injury with survival in five patients. JAMA 1985;253(2):243–5.
[59] Cooper MA, Price G. Electrical and lightning injuries. In: Mark JA, Hockburger RS, Walls RM, editors. Rosen’s Emergency Medicine: Concepts and Clinical Practices. 6th ed., St. Louis, MO: Mosby; 2006.
[60] Cherington M. Neurologic manifestations of lightning strikes. Neurology 2003;60(2):182–5.
[61] Muehlberger T, Vogt PM, Munster AM. The long-term consequences of lightning injuries. Burns 2001;27(8):829–33.
[62] Primeau M. Neurorehabilitation of behavioral disorders following lightning and electrical trauma. Neurorehabilitation 2005;20:25–33.
[63] van Zomeren AH, ten Duis HJ, Minderhoud JM, Sipma M. Lightning stroke and neuropsychological impairment: cases and questions. J Neurol Neurosurg Psychiatry 1998;64(6):763–9.
[64] Andrews CJ, Darveniza M. Telephone-mediated lightning injury: an Australian survey. J Trauma 1989;29(5):665–71.
[65] Sun GH, Simons JP, Mandell DL. Bilateral perilymphatic fistulas from a lightning strike: a case report. Laryngoscope 2006;116(6):1039–42.
[66] Gluncic I, Roje Z, Gluncic V, Poljak K. Ear injuries caused by lightning: report of 18 cases. J Laryngol Otol 2001;115(1):4–8.
[67] Gordon MA, Silverstein H, Willcox TO, Rosenberg SI. Lightning injury of the tympanic membrane. Am J Otol 1995;16(3):373–6.
[68] Jones DT, Ogren FP, Roh LH, Moore GF. Lightning and its effects on the auditory system. Laryngoscope 1991;101(8):830–4.
[69] Ogren FP, Edmunds AL. Neuro-otologic findings in the lightning-injured patient. Semin Neurol 1995;15(3): 256–62.
[70] Gupta A, Kaliaperumal S, Sengupta S, Babu R. Bilateral cataract following lightning injury. Eur J Ophthalmol 2006;16(4):624–6.
[71] Norman ME, Albertson D, Younge BR. Ophthalmic manifestations of lightning strike. Surv Ophthalmol 2001;46(1):19–24.
[72] Lee MS, Gunton KB, Fischer DH, Brucker AJ. Ocular manifestations of remote lightning strike. Retina 2002;22(6):808–10.
[73] Yi C, Liang Y, Jiexiong O, Yan H. Lightning-induced cataract and neuroretinopathy. Retina 2001;21(5):526–8.
[74] Cherington M, Kurtzman R, Krider EP, Yarnell PR. Mountain medical mystery. Unwitnessed death of a healthy young man, caused by lightning. Am J Forensic Med Pathol 2001;22(3):296–8.
[75] Cherington M, Krider EP, Yarnell PR, Breed DW. A bolt from the blue: lightning strike to the head. Neurology 1997;48(3):683–6.
[76] Cherington M, Breed DW, Yarnell PR, Smith WE. Lightning injuries during snowy conditions. Br J Sports Med 1998;32(4):333–5.
[77] Cherington M. Lightning injuries in sports: situations to avoid. Sports Med 2001;31(4):301–8.
[78] Cooper MA, Marshburn S. Lightning strike and electric shock survivors. Int Neurorehabil 2005;20(1):43–7.
[79] Committee on Trauma, American College of Surgeons. Resources for optimal care of the injured patient 2006. Chicago, IL: American College of Surgeons; 2006.
[80] Tieleman DP. The molecular basis of electroporation. BMC Biochem 2004;5:10.
[81] Bartholome CW, Jacoby WD, Ramchand SC. Cutaneous manifestations of lightning injury. Arch Dermatol 1975;111(11):1466–8.
[82] Bains N, Hoey J. Before lightning strikes. Can Med Assoc J 1998;159(2):163.
[83] Mann H, Kozic Z, Boulos MI. CT of lightning injury. Am J Neuroradiol 1983;4(4):976–7.
[84] Stanley LD, Suss RA. Intracerebral hematoma secondary to lightning stroke: case report and review of the literature. Neurosurgery 1985;16(5):686–8.
[85] Lehman LB. Successful management of an adult lightning victim using intracranial pressure monitoring. Neurosurgery 1991;28(6):907–10.
[86] Steinbaum S, Harviel JD, Jaffin JH, Jordan MH. Lightning strike to the head: case report. J Trauma 1994;36(1): 113–5.

[87] Cherington M, Yarnell P, Hallmark D. MRI in lightning encephalopathy. Neurology 1993;43(7): 1437–8.
[88] Milton WJ, Hal O'Dell R, Warner EG. MRI of lightning injury: early white matter changes associated with cerebral dysfunction. J Okla State Med Assoc 1996;89(3): 93–4.
[89] Freeman CB, Goyal M, Bourque PR. MR imaging findings in delayed reversible myelopathy from lightning strike. Am J Neuroradiol 2004;25(5):851–3.
[90] Cherington M. Lightning injuries. Ann Emerg Med 1995;25(4):517–9.
[91] Okafor UV. Lightning and acute renal failure: a review. Ren Fail 2005;27:129–34.